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Research article

Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe

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ABSTRACT

The majority of assessments of future heat-related health risk are based on projections of heat hazards superimposed solely on current socioeconomic conditions, thus neglecting the potential contribution of drivers of heat stress risk other than climate change. Partly to address this drawback, the climate change research community has developed a new scenario framework, made up of distinct sets of climate and socioeconomic scenarios. The few assessments of future heat-related health risk that have employed this new framework have focused on changes in population exposure but have often not accounted for future populations' vulnerability. In this paper, we combine European Shared Socioeconomic Pathways with Representative Concentration Pathways to provide spatially explicit European projections of heat-related health risk that account for multiple changes in both socioeconomic and climatic conditions. In doing so, we also address the challenge of accounting for projections of determinants of vulnerability under varying levels of socioeconomic development. Results reveal that the proportion of the European population at very high risk of heat stress will show a steady increase – from 0.4% currently to 20.3%, 32.6%, or 48.4% in 2050 depending on the scenario combination – unless substantial political changes occur rapidly and steadily shift the current socioeconomic development pathway towards sustainability. Ambitious mitigation policies associated with rapid technological progress to enhance human capital could also moderate future heat-related health challenges. Such challenges are unevenly spread across Europe, with the Mediterranean region and Scandinavia being respectively the most and the least impacted regions. Future heat-related health challenges are substantially influenced by varying levels of socioeconomic development, primarily through changes in vulnerability – changes in population exposure being only of secondary importance. The former may even have a more significant impact on future heat stress risk than climate change, particularly in the British Isles and in the Iberian Peninsula. Thus, there is an undeniable necessity to consider the future state of vulnerability – and its uncertainties under varying socioeconomic scenarios – when assessing future heat-related health challenges and designing health adaptation strategies.

1. Introduction

Heat waves are one of the most prominent climatic hazards (IPCC, 2012) as well as one of the most deadly (Hales et al., 2014), particularly in Europe (Forzieri et al., 2017). There is large evidence that climate change will lead to greater heat waves, in terms of frequency, intensity, duration, and spatial extent (Abaurrea et al., 2018; Dosio et al., 2018; Fischer and Schär, 2010), contributing to a substantial increase in heat-related health impacts such as heat exhaustion, heat stroke, and death (Amengual et al., 2014). The heat stress risk – and resulting health impacts – linked to these extreme temperature events rely not only on the heat hazard, but also on the exposure and vulnerability of the populations (Bao et al., 2015; Carter et al., 2014). It is widely acknowledged that a broad range of socioeconomic factors play an important role in the ability of populations to prepare for, respond to, and recover from heat waves – *i.e.* their vulnerability (Wilhelmi and Hayden, 2010).

However, while the influence of varying levels of climate forcing on future heat stress risk has been extensively explored (*e.g.*Gasparrini

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et al., 2017), to date there has been very little consideration of the potential role of changes in socioeconomic conditions. Projections of heat stress risk are traditionally based on future climatic conditions superimposed solely on current socioeconomic conditions (Dong et al., 2015). By taking this approach, the literature fails to account for future populations' vulnerability, which could potentially be very different from the current position and thus may significantly influence future heat-related health challenges (van Ruijven et al., 2013). Since health adaptation decision-making relies heavily on these assessments of heat stress risk, this standard practice is particularly problematic in that it misestimates the influence of climate change and neglects the role of socioeconomic changes, thus introducing a systematic bias into health management decisions (Ebi et al., 2016).

For some time it has been argued that projections of future heat-related health challenges must integrate future socioeconomic conditions and their associated uncertainties (Ebi, 2013; Ebi et al., 2016), through the use of scenarios (Preston et al., 2011). Such an approach is facilitated by the new scenario framework for climate change research (Moss et al., 2010), made up of a set of four greenhouse gases emissions trajectories (Representative Concentrations Pathways – RCPs, van Vuuren et al., 2011) and a set of five global socioeconomic development trends (Shared Socioeconomic Pathways – SSPs, O'Neill et al., 2013).This new framework has the potential to foster the use of socioeconomic scenarios within assessments of future climate risks (van Ruijven et al., 2013; Rothman et al., 2013). Developed in parallel, the RCPs and SSPs have been purposely designed to be combined in a scenario matrix architecture (van Vuuren et al., 2013) to explore future climate risks under multiple combinations of RCPs and SSPs (*i.e.* spanning a wide range of futures), assuming that a given RCP can be achieved by different SSPs. The latter have been quantified at the national level up to 2100 for key socioeconomic variables such as population and economic growth, urbanization, and education (Cuaresma, 2017; Jiang and O'Neill, 2017; KC and Lutz, 2014; Kc and Lutz, 2017).

In the past few years, combinations of RCPs and SSPs have been applied in a number of studies to assess future climate-related health impacts in the fields of agriculture and food security (*e.g.*Davenport et al., 2017; Hasegawa et al., 2014), water scarcity and flood risk (*e.g.*Veldkamp et al., 2016), exposure to vector-borne diseases (Monaghan et al., 2016), fire risk (Knorr et al., 2016), air pollution risk (Xu et al., 2015), and heat stress risk (*e.g.*Dong et al., 2015; Marsha et al., 2016). Despite this growing body of literature in the latter field, a number of research gaps and methodological issues still need to be explored.

First, the wide array of uncertainties in future heat-related health risk due to (*i*) the full range of plausible socioeconomic scenarios and (*ii*) their multiple possible combinations with the different RCPs is yet to be scrutinized. Indeed, existing studies have mostly focused until now on a sample of SSPs (*e.g.* two or three instead of the five contrasting socioeconomic development trends) and on a few selected combinations with RCPs that best suit their research needs. For instance, Anderson et al. (2016) and Marsha et al. (2016) explored future heat-related mortality under two contrasting SSPs (SSP3 and SSP5) that are of high interest to their regional focus (US cities), whereas Dholakia et al. (2015) and Kjellstrom et al. (2017) concentrated on the influence of different RCPs on future heat stress risk and therefore accounted only for a single SSP. Similarly, in their efforts to estimate future exposure and risk of deadly heat under three different levels of climate forcing, Dong et al. (2015), Liu et al. (2017), and Mora et al. (2017) used three integrated scenarios in which each RCP was paired with a different SSP, *e.g.* RCP2.6*SSP1, RCP4.5*SSP3, and RCP8.5*SSP5.

Second, future heat stress risk under multiple combinations of SSPs and RCPs has yet to be explored at high spatial resolution in Europe. So far, past studies applying the new scenario framework and covering Europe have been conducted with a coarse spatial resolution, often at a 0.5° spatial grid (Dong et al., 2015; Kjellstrom et al., 2017; Liu et al., 2017). Such lack of spatial detail may neglect significant local dynamics and may hinder their use by policy-makers to define suitable interventions on a regional scale.

Third, projections under the SSPs of the multiple determinants of vulnerability have yet to be integrated within assessments of future heat stress risk. Up to now, existing studies have mainly focused on hazard (heat) and population exposure, but have neglected the vulnerability of local populations (*e.g.*Chen et al., 2017; Matthews et al., 2017; Mishra et al., 2017). Most of the authors have acknowledged that future research should attempt to include additional variables that characterize future populations' vulnerability to heat (*e.g.*Anderson et al., 2016; Liu et al., 2017), but actual inclusion of such variables remains very rare. The integration of projections of vulnerability drivers into assessments of future heat stress risk has to date been limited to education, income level, age (Dong et al., 2015), urbanization (Rohat et al., 2017), and living arrangements of the elderly (Marsha et al., 2016), at a very coarse spatial resolution (county or national scale projections only).

Finally, and linked to the previous point, the influence of varying levels of socioeconomic development on future heat-related health challenges has yet to be explored in light of changes in future populations' vulnerability. So far, such influence has been quantified only with regard to changes in future populations' size (*e.g.*Coffel et al., 2017; Jones et al., 2018; Liu et al., 2017; Rohat et al., In review).

In view of these research gaps and of the need to provide policy-relevant information about future heat-related health challenges in Europe (Forzieri et al., 2016), the aims of this paper are multiple. First, it aims to provide spatially explicit European projections of heat-related health risk that account for multiple changes in both socioeconomic and climatic conditions. Second, by doing so, this paper also aims to (*i*) address the challenge of accounting for projections of the wide array of vulnerability determinants, (*ii*) explore the full range of uncertainties through the use of multiple combinations of SSPs and RCPs, and (*iii*) investigate the influence of varying levels of socioeconomic development on future heat-related health challenges, mainly through changes in vulnerability.

2. Methods and data

2.1. Climate and socioeconomic scenarios

In this paper, we accounted for uncertainty in future climatic conditions through the use of three different emissions pathways, namely RCP2.6, RCP4.5, and RCP8.5 (van Vuuren et al., 2011). RCP2.6 leads to a very low concentration of greenhouse gases, assuming a substantial reduction of emissions and ambitious mitigation policies, in which the mean global temperature shows an increase of 0.4–1.6 °C by mid-century (relative to 1986–2005). RCP4.5 is a stabilization scenario leading to a global temperature increase of 0.8–1.8 °C by the 2050s. RCP8.5 is a high-emission scenario, under which the mean global temperature shows an increase of 1.4–2.6 °C by the 2050s (IPCC, 2014).

To account for uncertainty in future socioeconomic conditions, we used four different socioeconomic scenarios. The global SSPs are seen as an up-to-date set of global socioeconomic development trends that provide a global context for climate change research at global and regional levels (O'Neill et al., 2017), but they need to be extended – *i.e.* contextualized and quantified for specific regions and/or sectors – to increase their suitability for regional and sectoral studies as well as their relevance for policy-making and intake by local stakeholders (Absar and Preston, 2015).

In this study, we make use of the extended SSPs for Europe (hereafter SSP_{EU}), which have been developed in the IMPRESSIONS project (Kok and Pedde, 2016; Kok et al., 2018) and have been further extended for sectors relevant to social vulnerability based on a scenario matching approach with multiple existing sets of European scenarios (Rohat et al., In review). The $SSPs_{EU}$ are consistent with the global SSPs' narratives but contain far more regional detail about future European socioeconomic development trends. It should be noted that SSP2 –

Table 1
Determinants of socioeconomic vulnerability to heat stress in Europe.

Determinant	Proxy	Rationale
Income	Gross Domestic Product (GDP) *per capita* at Power Purchase Parity (PPP)	At the level of individuals, higher income means greater ability to protect against heat stress, *e.g.* by having greater access to useful information and self-protective resources such as air conditioning and efficient housing insulation (Lundgren and Kjellstrom, 2013). At the regional level, high-income populations are usually associated with wealthy regions, which have the financial capability to provide better infrastructure to cope with extreme temperature events (Hajat and Kosatky, 2010).
Education	% of people aged 24–65 years old with tertiary education	Important determinant of adaptive capacity towards climate change impacts (Muttarak and Lutz, 2014). At the level of individuals, higher education is frequently associated with higher awareness and knowledge of risk prevention (Vescovi et al., 2005), whereas low education has been directly linked to higher mortality risk in relation to heat hazard (Steenland et al., 2002). At the regional level, highly educated populations commonly lead to greater capacity for innovation and technological strength, positively linked to the ability to mitigate climate risks (Lutz et al., 2014).
Ageing	% of people over 65 years old	At the level of individuals, ageing lowers people's ability to properly thermoregulate their bodies and to adjust to high temperature changes (Inbar et al., 2004), resulting in a higher risk of heat-related illness and death during extreme temperature events (D'Ippoliti et al., 2010; Fouillet et al., 2006). At the regional level, a higher proportion of elderly people increases the pressure on health care and on emergency services during heat waves.
Artificial surfaces	% of artificial surfaces	Has the potential to increase the risk of heat-related illness due to its heating effect (Bradford et al., 2015; Reid et al., 2009). It is in particular the lack of green spaces and the predominance of impervious cover which lead to higher air temperatures, due to the urban heat island effect (Oleson et al., 2013).
Social isolation	% of people over 65 years old living alone	Considerably increases heat-related death risk among elderly (Fouillet et al., 2006; Vandentorren et al., 2006). Elderly people who live alone have fewer social contacts, lower access to transportation, and lack of support in extreme heat events (Lung et al., 2013; Romero-Lankao et al., 2012).
Pre-existing medical conditions	% of people over 18 years old overweight (Body Mass Index > 25)	Increases individuals' sensitivity to heat stress risk (Rocklöv et al., 2014). Pre-existing medical conditions that influence heat stress risk include a broad range of diseases affecting cardiovascular and renal functions (Stafoggia et al., 2006), mental health conditions (Foroni et al., 2007), cerebrovascular functions (Stafoggia et al., 2008), diabetes, and overweight (Semenza et al., 1999). Heatstroke occurs more frequently in adults with overweight (Kenny et al., 2010). Overweight is also highly correlated with type 2 diabetes (CDC, 2017), which also leads to higher death risk during heat waves (Schwartz, 2005).

which represents a “middle-of-the-road” type of socioeconomic development – was not extended for Europe, mainly due to its lack of relevance for this region and to the absence of comparable existing scenarios (Kok et al., 2015). In a nutshell, $SSP1_{EU}$ depicts a strong and sustainable Europe where the emphasis is on human well-being rather than on economic growth, with strong commitments to achieving the Sustainable Development Goals through environmental awareness, reduced inequalities, and less resources-intensive lifestyles. In contrast, $SSP3_{EU}$ depicts a broken Europe with resurgent nationalism and competition, gloomy economic conditions and materialistic lifestyles, associated with a disintegration of the social fabric. $SSP4_{EU}$ describes a highly unequal Europe, where power and the benefits of economic growth are reserved for a small political and business elite, while a large part of the population is left behind with a low level of development and does not benefit from investments in health, education, and environmental protection. Finally, $SSP5_{EU}$ depicts a strong Europe with steady economic growth, competitive markets, and rapid technological progress to enhance human capital, relying on an intensive exploitation of fossil fuel resources and associated with low concerns for global environmental issues as well as consumption-intensive lifestyles (see appendix A for further details on the $SSPs_{EU}$).

2.2. Heat stress risk framework

This paper adopts the latest conceptualization of risk described in the 5th Assessment Report of the Intergovernmental Panel on Climate Change – IPCC AR5 (IPCC, 2014), which characterizes heat stress risk as being the combination of heat hazard, vulnerability (population's abilities to prepare for, respond to, and recover from heat hazard), and exposure (presence of people).

2.2.1. Hazard

A large number of heat hazard indices have been developed and applied in heat stress risk assessments over the past decades (Perkins, 2015). In this paper, we used heat waves days (Dong et al., 2015; Fischer and Schär, 2010; Liu et al., 2017) and considered the heat hazard index as being the number of heat wave days (*HWDs*) during summer months (June, July, and August) over a given time period. We defined *HWDs* as the total number of days in a season (summer) that exceed a predefined threshold for at least 6 consecutive days (Dong et al., 2015). Considering the diversity of climatic zones in Europe, the use of either a fixed or a relative threshold may be problematic as the former can lead to overestimating heatwave length in warm climates, and the latter to unrealistically “cold” heatwave at higher latitude. In this study we set the threshold at the local 90th percentile of daily maximum temperature – centered on a 15-days window – over the reference period (Fischer and Schär, 2010). However, if the local 90th percentile is $< 25\,^{\circ}C$, then a fixed threshold of $25\,^{\circ}C$ was applied (similarly to Dong et al., 2015; Liu et al., 2017). Humidity was not accounted for because recent findings suggest that its contribution to deadly heat waves in Europe is negligible (Russo et al., 2017).

To compute *HWDs*, we used projections of daily maximum temperature for the summer months retrieved from seven high-resolution (0.11°) regional climate model (RCM) simulations (full list in appendix B) from the Coordinated Regional Climate Downscaling Experiment for Europe (EURO-CORDEX, Jacob et al., 2014). EURO-CORDEX runs have been extensively validated (*e.g.*Kotlarski et al., 2014), their abilities to simulate present-day heat waves have been assessed (Russo et al., 2015; Vautard et al., 2013), and they have been widely used to analyze projections of extreme temperatures (Dosio, 2016; Dosio and Fischer, 2018). Daily projections were retrieved for the summer months of the period 2041–2060 – to represent year 2050 – and historical runs were used for simulating the baseline climate (1986–2005). *HWDs* was computed for all combinations of RCMs and RCPs (as well as for the baseline period), yielding an ensemble of 28 different model/scenario combinations. These were then spatially interpolated on a 0.1° spatial

grid.

2.2.2. Vulnerability and exposure

Because one of the aims of this paper is to encourage the consideration of future vulnerability when assessing future climate risks, we accounted for a range of variables that seek to represent comprehensively the different dimensions of heat-related vulnerability (Table 1). Despite the growing number of heat-related mortality studies conducted in Europe – *e.g.*Åström et al. (2017) – there is still a lack of comprehensive and fine-scale epidemiological data on heat-related mortality at the European level. Therefore, determinants of vulnerability were chosen based on a deductive approach (Yoon, 2012) informed by local epidemiological studies. Exposure is accounted for through the presence (or absence) of population (IPCC, 2012) in each unit of analysis (see section 2.2.3).

The lack of quantitative and spatially explicit projections of socioeconomic variables under the SSPs is one of the main obstacles to the integration of socioeconomic scenarios within climate risk assessments. In this paper, we relied on innovative projection exercises to obtain spatially explicit projections of the six socioeconomic variables set out in Table 1 and of future population (see appendix C for more details on the projection exercises).

In summary, population and GDP projections were retrieved from the recent downscaling exercise of the Joint Research Center of the European Commission, which provides projections consistent with the $SSPs_{EU}$ at a 0.1° spatial resolution (Hurth et al., 2017; Lückenkötter et al., 2017). Projections of proportions of artificial surfaces, produced within the IMPRESSIONS project (Berry et al., 2017), were retrieved from Terama et al. (2017). These were made on a 10′ lat/lon spatial grid (~13*13 km) using a regional urban growth model parametrized with assumptions of age group-specific residential preferences under the four $SSPs_{EU}$. Age-specific population projections at sub-national level (NUTS-2 regions) were also retrieved from the IMPRESSIONS project – described in Terama et al. (2017) and available in Terama and Clarke (2016) – and were further downscaled on a 0.1° spatial grid based on current figures.

Projections of education levels were retrieved from the quantification of the global SSPs at national scale (KC and Lutz, 2017), were then further downscaled to the NUTS-2 level based on current figures, and were finally disaggregated to a 0.1° spatial grid assuming a homogeneous proportion of people with higher education within each NUTS-2 region.

Consistent projections of overweight prevalence and of the proportion of elderly living alone were nonexistent in Europe – only a few short-term predictions at national and continental levels have been made (Doblhammer and Ziegler, 2006; Gaymu et al., 2008; Webber et al., 2014). To deal with this lack of available data, we carried out an innovative expert-based modeling approach, detailed in Rohat (2018).

Briefly, to project the overweight prevalence, we (*i*) retrieved current figures at national level, (*ii*) disaggregated them at the NUTS-2 level based on age group-specific statistics of overweight prevalence (*iii*), further downscaled them on a 0.1° spatial grid based on urbanization-specific overweight figures, (*iv*) projected these downscaled statistics based on changes in both age group structure and urbanization level under the four $SSPs_{EU}$, and (*v*) revised these projections with adjustment factors determined through the quantification of experts' judgments (retrieved *via* an online questionnaire) using the fuzzy set theory approach (Eierdanz et al., 2008; Pedde et al., 2018). We applied a similar procedure to project the proportion of elderly people living alone, except that we initially used current figures at the NUTS-3 level and did not apply the age groups- and urbanization-based downscaling.

Each variable was then normalized – spatially and temporally – using a linear min-max rescaling and combined into a vulnerability index using an additive approach with equal weights (further discussed in appendix D and in Section 4.3). We computed the vulnerability index under current (2015) socioeconomic conditions (referred to below as the baseline) and under the four $SSPs_{EU}$ for the year 2050.

2.2.3. Integrated heat stress risk

We employed the method described in Lung et al. (2013) and computed heat stress risk based on the geometric aggregation of hazard (*HWDs*) and vulnerability (vulnerability index). Both were normalized in advance – spatially and temporally – using a z-score rescaling with a factor-10 shift, because geometric aggregation requires non-zero positive values (OECD, 2008). Other types of aggregation approach were also used to explore the robustness of the results (see Section 4.3). Using a similar approach as Dong et al. (2015), we validated the integrated heat stress risk framework at the country level with heat wave mortality data from the baseline period (1986–2005) and during the 2003 European heat wave, retrieved from the Emergency Event Database (EM-DAT: http://www.emdat.be) and from Robine et al. (2008). Through linear regression analyses (see appendix E), we highlighted the correlation between death counts and estimated heat stress risk, although a comparison at the national level is likely to hide some local level correlations (Lung et al., 2013).

We computed heat stress risk at the grid cell level and employed a 0.1° spatial grid (see Sections 2.2.1 and 2.2.2) – on which all the socioeconomic and climatic data have been interpolated beforehand – covering 8 European regions (sub-domains of the EURO-CORDEX spatial grid) and 25 of the EU-28 member countries (see appendix F). The resulting values of heat stress risk were then classified (deciles-based) and population figures were used to determine the number of persons per risk class, with a focus on the number of people at high or very high risk. We excluded from the risk assessment places where exposure was nil (*i.e.* where no one lives), meaning that we discarded grid cells in which the population density was < 1 inhab.km^{-2}.

We computed future heat stress risk for the year 2050 under all the combinations of $SSPs_{EU}$ and RCPs, exception made of the few inconsistent combinations – RCP8.5*SSP1, RCP2.6*SSP3, and RCP2.6*SSP5 – for which the emissions level of the RCP is very unlikely to be reached by the socioeconomic development depicted in the SSP. In addition, we computed current heat stress risk, represented by baseline socioeconomic and climatic conditions, as well as heat stress risk for the year 2050 assuming either (*i*) fixed socioeconomic conditions (*i.e.* combinations of RCPs with baseline socioeconomic conditions), or (*ii*) fixed climatic conditions (*i.e.* combinations of $SSPs_{EU}$ with baseline climate). These combinations allow a better exploration of the individual effect of changes in socioeconomic and climatic conditions on future heat stress risk. We performed the risk assessment for each of the 7 RCM simulations independently and used the multi-model-median values (Petkova et al., 2016) to explore heat stress risk across the 17 aforementioned scenario combinations.

3. Results

3.1. Heat hazard

The spatially averaged number of heat wave days (*HWDs*) in Europe for a given time period varies greatly from one RCP to another and from one RCM simulation to another. To emphasize the impact of the three RCPs on future heat hazard, we used the multi-model-median values of *HWDs* (averaged over the 20-year summer periods). Variability across the 7 different RCMs simulations is displayed through the interquartile range (*bracketed*).

Results show that the heat wave area over Europe – computed as the percentage of grid cells with at least one heat wave per time period – increases from 77.6% (*13.5*) in the baseline period to 82.7% (*7.4*) and 84% (*9.8*) in the 2050s under RCP4.5 and RCP8.5 respectively, but stabilizes under RCP2.6.

Spatial patterns of *HWDs* (Fig. 1) depict a clear North-to-South latitudinal gradient. Northern Scandinavia has a multi-model-median spatial mean *HWDs* per summer of < 1 (*0.4*) under all RCPs, while in

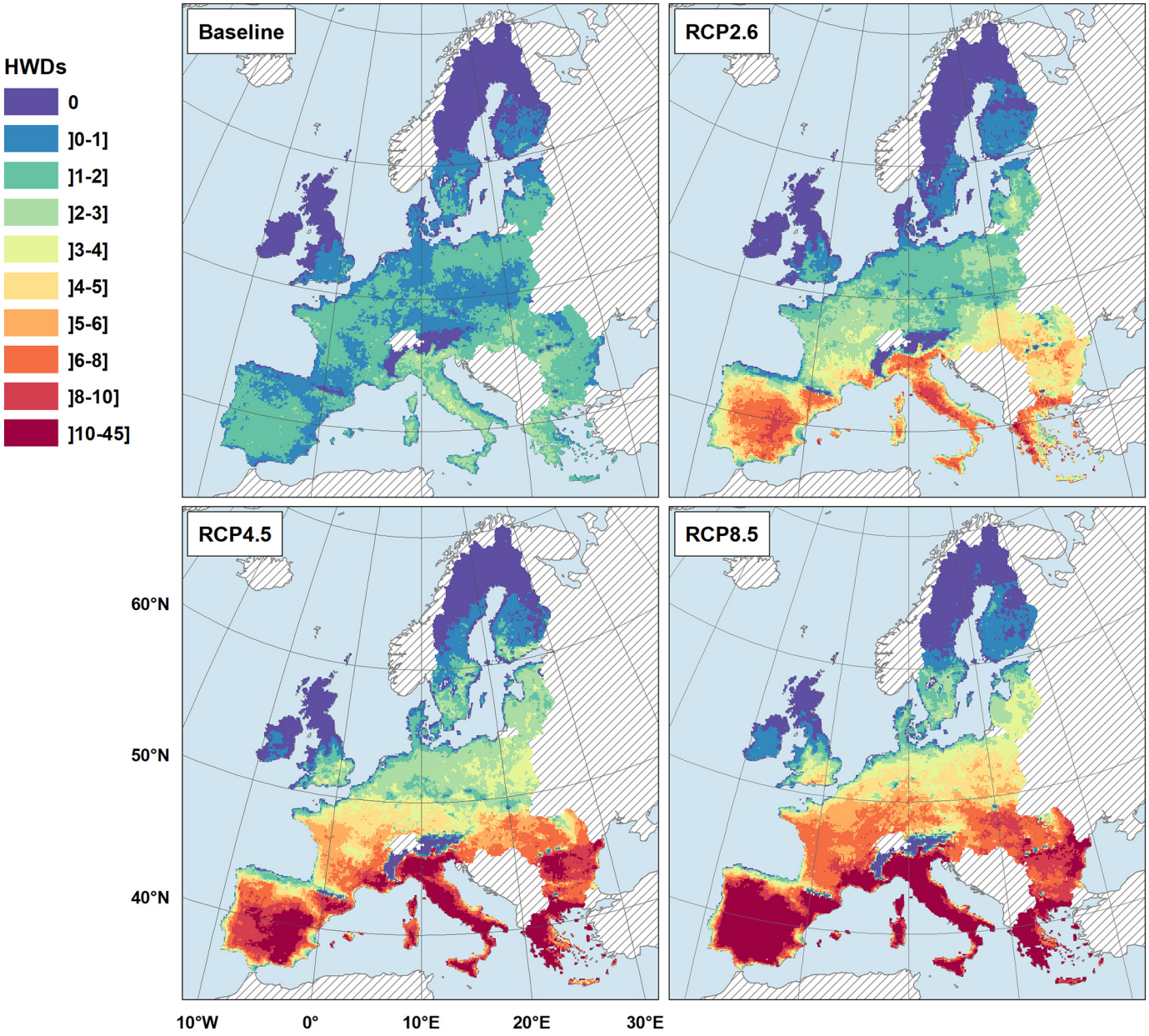

Fig. 1. Mean number of summer heat wave days (HWDs) for the baseline (1986–2005) and future (2041–2060) conditions under three RCPs. Results are shown as multi-model ensemble median. The model variability is shown in Appendix G.

the Mediterranean region the multi-model-median spatial mean *HWDs* per summer under RCP4.5 and RCP8.5 are respectively 10.2 (*4.3*) and 12.3 (*5.0*). The heat wave area in Southern Europe (Mediterranean region and the Iberian Peninsula) is significantly higher than in Northern Europe (Scandinavia and the British Isles) under all RCPs, rising up to 99.4% (*1.9*) under RCP8.5 (compared to 65.9% (*21.2*) in Northern Europe under the same RCP). Finally, certain parts of Scandinavia, of the British Isles, and of the Alps show no *HWDs* under all models and scenarios – due to the minimum fixed threshold of 25 °C –, whereas most of the grid cells of the Iberian Peninsula and of the Mediterranean region show > 10 *HWDs* per summer under all models and RCPs.

3.2. Socioeconomic vulnerability and exposure

Results show that the individual determinants of socioeconomic vulnerability – and thus the composite vulnerability index – are significantly affected by the varying levels of socioeconomic development depicted under the four $SSPs_{EU}$, while population exposure at the grid-cell level (expressed here in terms of population density) only shows minor changes compared to the baseline condition (Fig. 2; full results available in appendix H). At the European level however, the global population of the 25 investigated countries shows substantial changes, rising from 493 million in 2015 up to 536 million and 602 million in 2050 under $SSP1_{EU}$ and $SSP5_{EU}$ respectively, stabilizing under $SSP4_{EU}$, and declining to 446 million under $SSP3_{EU}$, mainly due to unfavorable economic conditions and low immigration. The fairly high population growth under $SSP5_{EU}$ (+18.2% compared to baseline) leads to both higher population density and increased proportion of artificial surfaces, also enabled by the lack of restrictive planning regulations. Under $SSP1_{EU}$, lower population growth (+8.1%) and efficient planning both limit further expansion of artificial surfaces.

The European population ages under all $SSPs_{EU}$, with the highest ageing rate occurring under $SSP1_{EU}$ and $SSP4_{EU}$, mainly due to limited immigration. The proportion of elderly people under all $SSPs_{EU}$ (except $SSP5_{EU}$) rises up to 60–65% in the Mediterranean region, in the Iberian

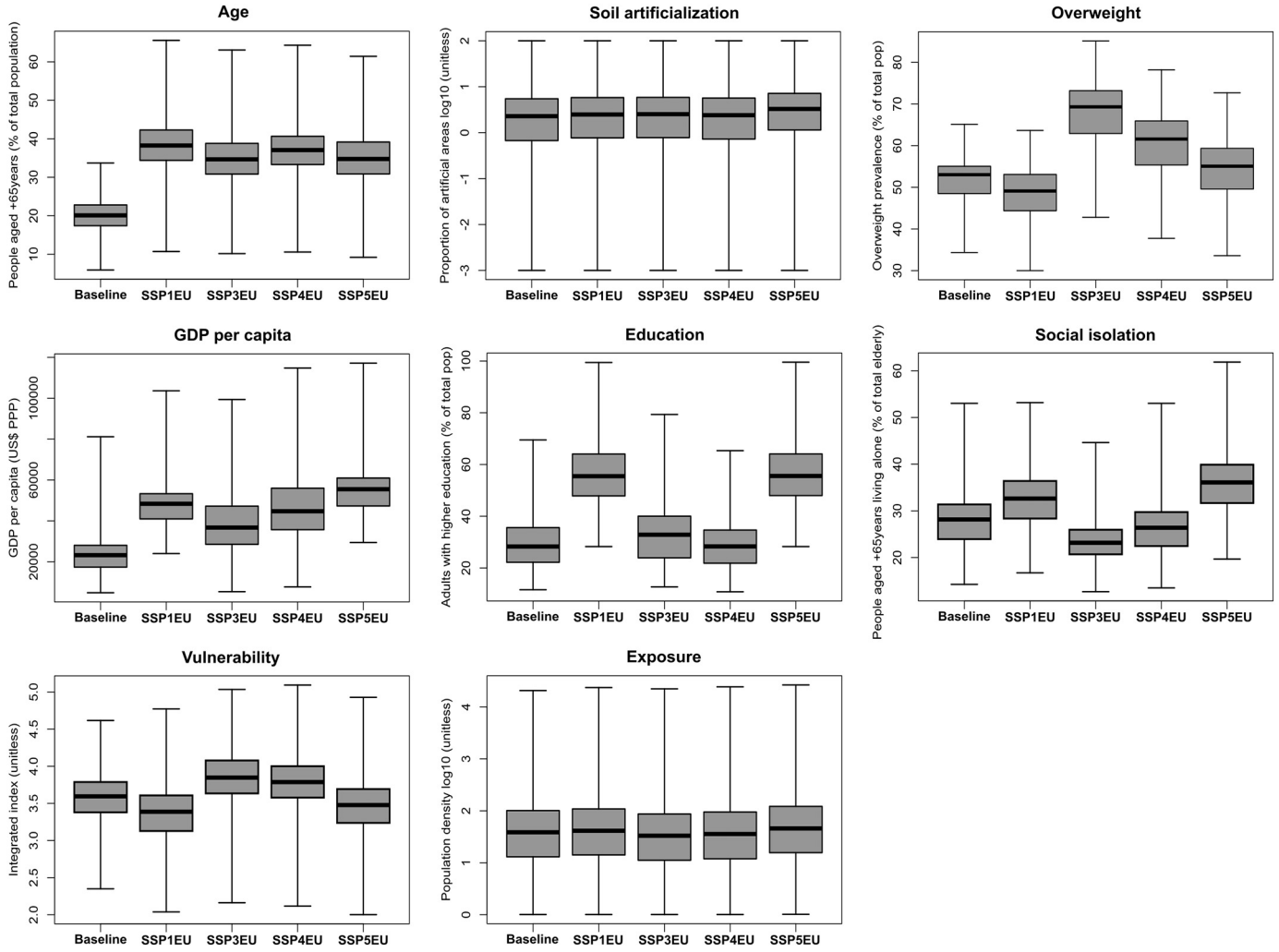

Fig. 2. Spatial distribution of the six drivers of vulnerability, the vulnerability index, and population exposure at the grid-cell level, for baseline socioeconomic conditions and for the year 2050 under the four $SSPs_{EU}$.

Peninsula, and in the Southern part of Eastern Europe, whereas the current proportion in these regions is < 30%.

In addition to ageing, the elderly's living arrangements also change significantly. While the proportion of elderly people living alone decreases under $SSP3_{EU}$ and $SSP4_{EU}$ – with an average of 23.5% and 26.4% respectively, compared to 27.8% currently –, it rises under the two other scenarios. The highest increase occurs under $SSP5_{EU}$, in which on average 35.8% of the elderly are living alone, a proportion which increases to 50–60% in Scandinavia.

Based on a continuous economic growth, GDP *per capita* increases under all $SSPs_{EU}$, with the highest increase taking place under $SSP5_{EU}$. In the case of the latter, GDP *per capita* rises up to 54′900 US$ on average (meaning an increase of +58% compared to the current economic situation), with major cities of the British Isles, of France, and of Mid-Europe having a GDP *per capita* higher than 100′000 US$. In contrast, economic growth is fairly limited under $SSP3_{EU}$, with a growth in mean GDP *per capita* of +37% compared to the baseline. Due to assumptions of strong economic divergence under $SSP3_{EU}$ and $SSP4_{EU}$, the poorest regions at the present time (*e.g.* rural regions in Eastern Europe) are expected to experience economic stagnation under these scenarios. The significant inequalities depicted under $SSP4_{EU}$ are reflected in the very large spread of GDP *per capita*, ranging from < 8′000 US$ in several regions of Eastern Europe to > 110′000 US$ in wealthy centers of the British Isles and of Mid-Europe. In contrast, assumptions of economic convergence under $SSP1_{EU}$ lead to a smaller range between extreme values of GDP *per capita* (minimum of 24′000 US$ and maximum of 103′000 US$).

In relation to education level, $SSP1_{EU}$ and $SSP5_{EU}$ both lead to a very high increase – due to considerable investment in education –, with 57.3% and 57.4% respectively of European adults having completed their tertiary education. In several urbanized regions of France and of the British Isles, this rate exceeds 90%. In contrast, $SSP3_{EU}$ and $SSP4_{EU}$ do not lead to a significant increase in education, with 32.7% and 28.1% respectively of adults having completed tertiary education, compared to 28.8% currently. The slight decrease observed under $SSP4_{EU}$ is primarily due to significant inequalities in terms of investments and access to education, with only small political and business elites benefitting.

In contrast to education, the prevalence of overweight increases considerably under $SSP3_{EU}$ and $SSP4_{EU}$, with 68.5% and 60.8% respectively of the European adult population being overweight in 2050, compared to 51.9% currently. A slightly lower increase is expected under $SSP5_{EU}$ (54.7% on average), while overweight prevalence decreases under $SSP1_{EU}$ (48.9% on average) and reaches < 35% in certain parts of Scandinavia.

As a result of all the trends discussed above, the vulnerability index increases under $SSP3_{EU}$ and $SSP4_{EU}$, but decreases under $SSP1_{EU}$ and $SSP5_{EU}$. The high vulnerability area – computed as the proportion of grid cells within the 8th–10th deciles – increases from 22.4% (in 2015) to 46.7% and 54.5% in 2050 under $SSP4_{EU}$ and $SSP3_{EU}$ respectively,

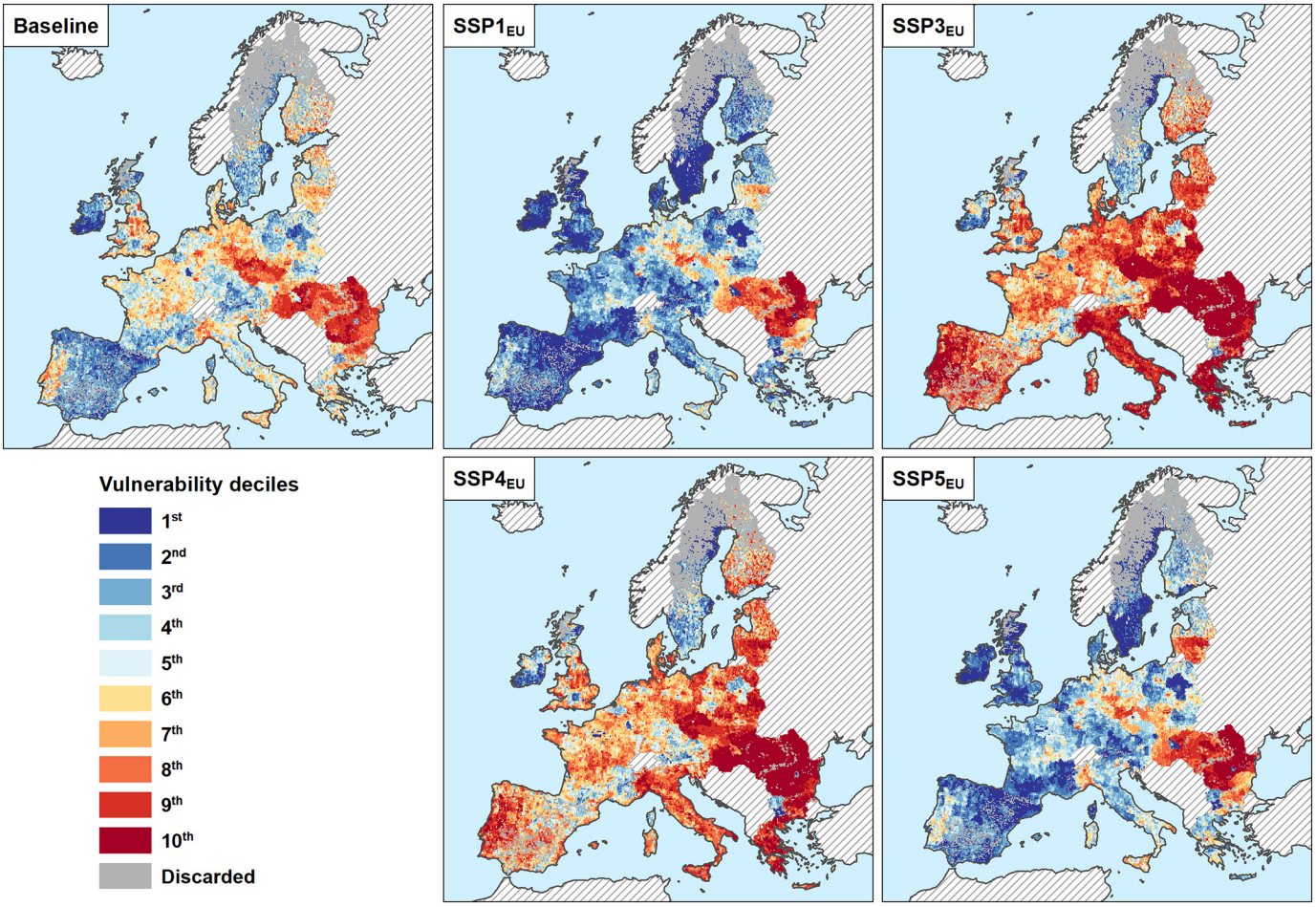

Fig. 3. Vulnerability index in Europe for the baseline socioeconomic conditions (2015) and for the year 2050 under the four $SSPs_{EU}$. Classification by deciles – over all scenarios and time-periods.

while the low vulnerability area – computed as the proportion of grid cells within the 1st-3rd deciles – increases from 28.4% currently to 43.2% and 53.8% in 2050 under $SSP5_{EU}$ and $SSP1_{EU}$ respectively. The highest vulnerability levels are found in certain parts of Eastern Europe, under $SSP4_{EU}$ (Fig. 3). These regions, together with certain parts of Mid-Europe, display very high vulnerability (9th–10th deciles) under all scenarios as well as in the baseline situation. Similarly, most of the investigated regions of Scandinavia and of the North of the British Isles show very low vulnerability (1st-2nd deciles) in most cases. In contrast, the Mediterranean region and the Iberian Peninsula are highly scenario-sensitive, showing very high vulnerability under $SSP3_{EU}$ and $SSP4_{EU}$ and very low vulnerability under $SSP1_{EU}$ and $SSP5_{EU}$.

3.3. Future heat stress risk

The 17 combinations of climatic and socioeconomic conditions lead to significantly different levels of heat stress risk (see appendix I for the full results). As expected, combinations of low radiative forcing (RCP2.6) with socioeconomic scenarios depicting lowly vulnerable populations ($SSP1_{EU}$) lead to the lowest future risk levels and to the highest proportion of areas at very low risk (1st-2nd deciles), covering 36.6% of the spatial grid. By contrast, combinations of high radiative forcing (RCP8.5) with $SSPs_{EU}$ depicting highly vulnerable populations ($SSP3_{EU}$ and $SSP4_{EU}$) lead to the highest future risk levels and to the highest proportion of areas at very high risk (9th–10th deciles), covering 49% and 45% respectively of the total area analyzed. Compared to the present situation, the latter increases under all scenario combinations, including those assuming a medium radiative forcing and a society with a low level of vulnerability – *e.g.* rising from < 1% in Baseline*Baseline to 14% and 19% under RCP4.5*$SSP1_{EU}$ and RCP4.5*$SSP5_{EU}$ respectively.

3.3.1. Spatial clusters of risk across the multiple scenario combinations

Under each scenario combination, future heat stress risk exhibits large spatial disparities (Fig. 4). Scandinavia and the British Isles show a very low risk (1st-2nd deciles, *i.e.* 1st quintile) under all the scenario combinations, due to both a very low heat hazard under all of the RCPs and to lowly vulnerable populations under all the $SSPs_{EU}$. Similarly, the Southern part of Eastern Europe and certain parts of the Mediterranean region show a very high risk (9th–10th deciles, *i.e.* 5th quintile) under all the scenario combinations, due to both a high heat hazard under all the RCPs and very vulnerable populations under all the $SSPs_{EU}$, including $SSP1_{EU}$ and $SSP5_{EU}$.

In contrast, a large number of European regions exhibit very different risk levels across the multiple scenario combinations. For instance, the Iberian Peninsula shows on average a low risk (3rd-4th deciles, *i.e.* 2nd quintile) under RCP2.6*$SSP1_{EU}$, a moderate risk (5th–6th deciles, *i.e.* 3rd quintile) under RCP4.5*$SSP1_{EU}$/$SSP5_{EU}$, a high risk (7th–8th deciles, *i.e.* 4th quintile) under RCP8.5*$SSP5_{EU}$ and RCP2.6*$SSP4_{EU}$, and a very high risk under RCP4.5/RCP8.5*$SSP3_{EU}$/$SSP4_{EU}$. Similarly, most of Mid-Europe is highly sensitive to changes in scenario combinations, showing globally a very low and low risk under RCP2.6*$SSP1_{EU}$ and RCP4.5*$SSP1_{EU}$/$SSP5_{EU}$ respectively, and a high risk under RCP4.5/RCP8.5*$SSP3_{EU}$/$SSP4_{EU}$. Finally, it is worth noting that under the combinations RCP4.5/RCP8.5*SSP3EU/SSP4EU, most of the Mediterranean region, the Iberian Peninsula, and the Southern part

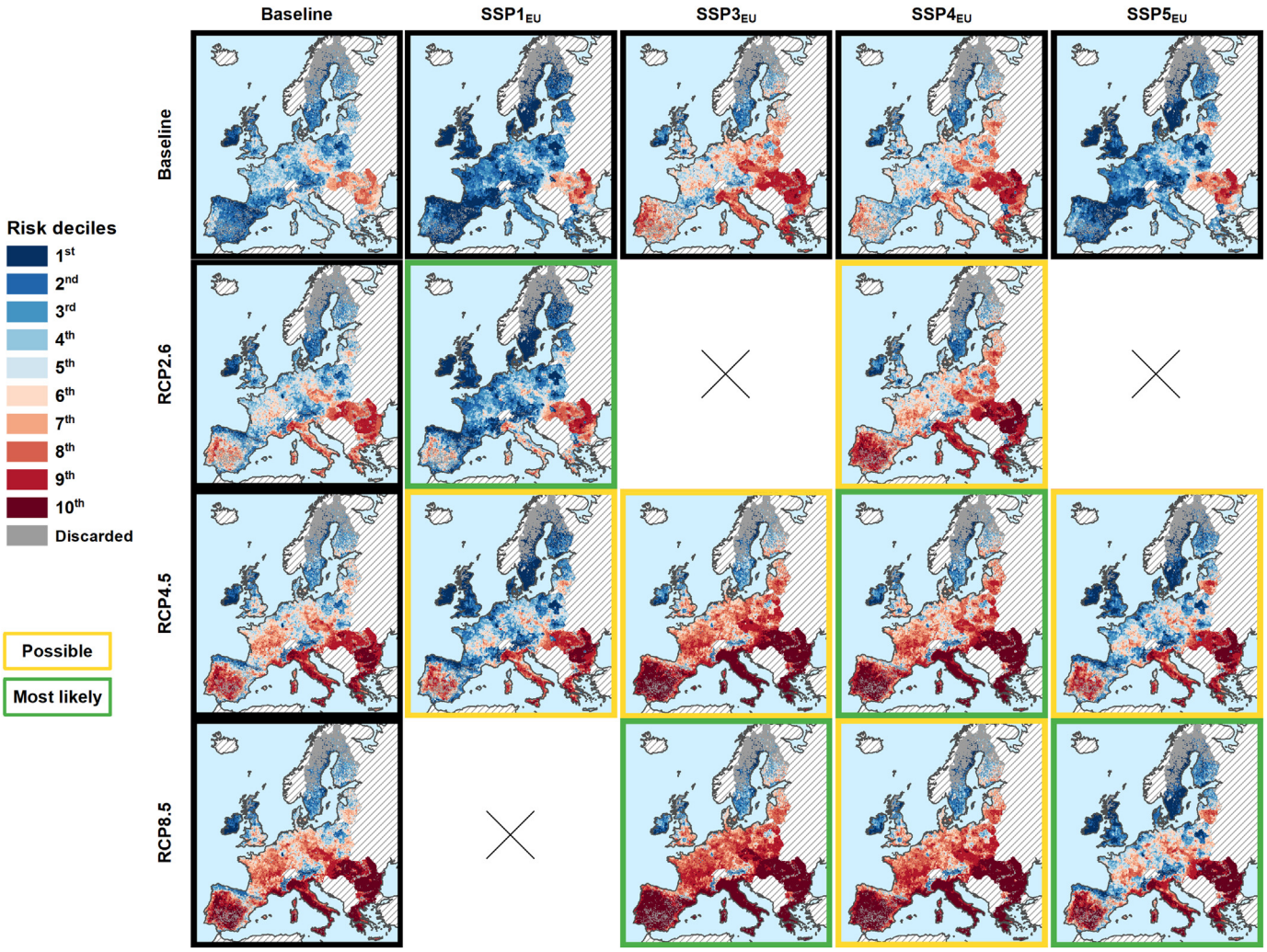

Fig. 4. Scenario matrix representing the spatially explicit multi-model-median heat stress risk for the 17 scenario combinations. Classification by deciles. Colors of the frames indicate the plausibility of the scenario combination (no color (black) is given for combinations with baseline climate and/or baseline socioeconomic conditions).

of Eastern Europe are at very high risk of heat stress, whereas at present they generally show a very low or low risk.

3.3.2. *Populations exposed to very high risk*

Combined with population projections, the steady increase of heat stress risk in Europe leads to a substantial increase in the number of people at very high risk of heat stress under three of the most likely futures (Fig. 5). Results show that in the current situation (Baseline*Baseline), only 2.1 M (million) people (0.4% of the total population) are at very high risk. This number increases up to 161 M (32.6%) under RCP4.5*$SSP4_{EU}$ and to 216 M (48.4%) under RCP8.5*$SSP3_{EU}$. Such an increase is more moderate under RCP8.5*$SSP5_{EU}$ and very limited under RCP2.6*$SSP1_{EU}$, each scenario combination leading to, respectively, 122 M (20.3%) and 12.9 M (2.4%) people at very high risk. Further results (see appendix I) also show that most of the population at very high risk is located in the Mediterranean region, the Iberian Peninsula, and the Southern part of Eastern Europe. Under RCP8.5*$SSP3_{EU}$/$SSP4_{EU}$, certain urban centers of Mid-Europe and of France also show a large number of people at very high risk.

3.3.3. *Individual influence of RCPs and $SSPs_{EU}$*

To explore the individual influence of climate and socioeconomic scenarios on future heat-related health challenges, we computed the changes in the number of people at high or very high risk for each European sub-domain compared to the baseline conditions, separately for each RCP (*i.e.* across the first column of the scenario matrix) and for each SSP_{EU} (*i.e.* across the first row of the scenario matrix). Results (Fig. 6) show that climate scenarios alone tend to have a greater impact on the future number of people at high/very high risk than socioeconomic scenarios alone in most of the sub-domains. This is mainly explained by the fact that the expected changes in heat hazard (compared to baseline) under the RCPs (particularly under RCP4.5/RCP8.5) are often greater than the changes in vulnerability (compared to baseline) depicted under the $SSPs_{EU}$. However, the potential benefits of a substantial decrease in vulnerability (as expected under $SSP1_{EU}$ and $SSP5_{EU}$) may be underestimated under current climatic conditions, due to the current small proportion of people at high/very high risk. The positive influence of $SSP1_{EU}$ and $SSP5_{EU}$ might be much greater when combined with an increased heat hazard (further discussed in Section 4.2).

Nonetheless, results show that changes in socioeconomic conditions still largely affect future heat-related health challenges, particularly in places where socioeconomic conditions are projected to change significantly (*e.g.* the Iberian Peninsula and Eastern Europe) and in regions where the heat hazard is expected to remain low (*e.g.* Scandinavia). In the Iberian Peninsula, while only 0.05 M people are currently at high/very high risk (0.1% of the regional population), the socioeconomic changes depicted in $SSP3_{EU}$ and $SSP4_{EU}$ lead to an increase of

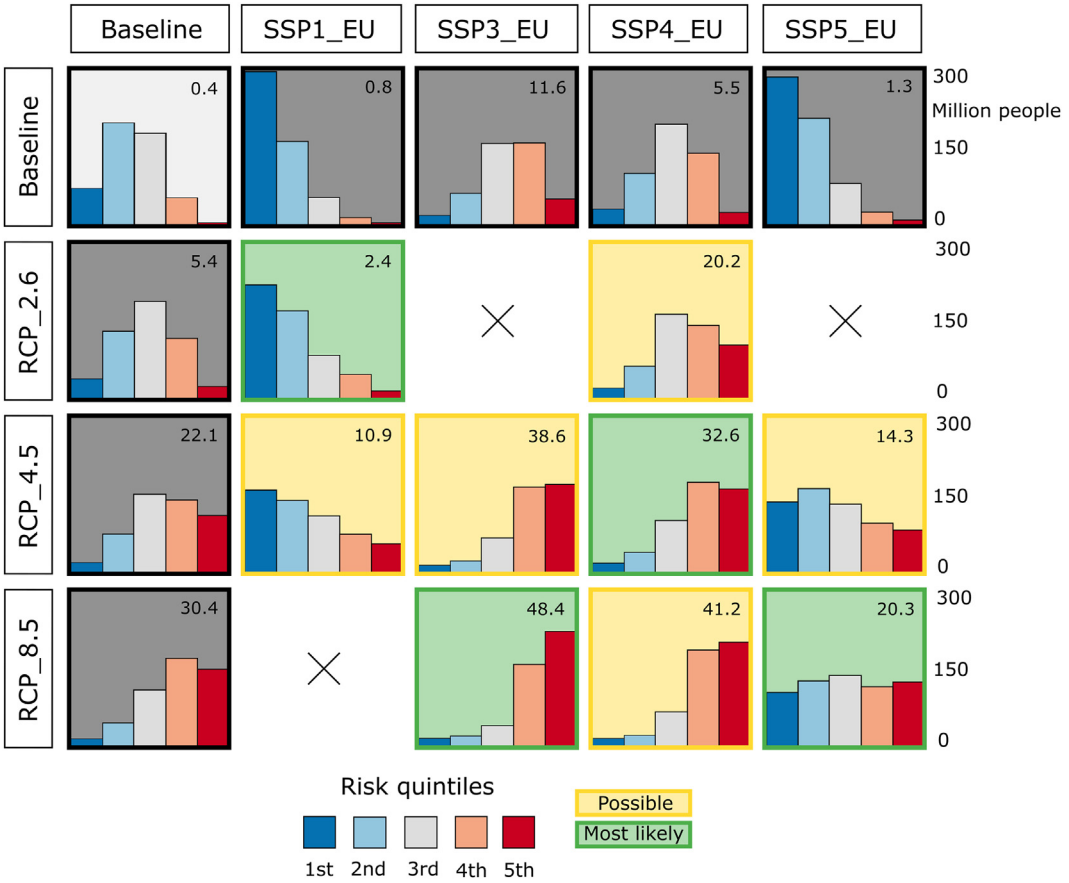

Fig. 5. Scenario matrix representing the number of people (in millions) per quintile of heat stress risk – from very low (1st) to very high (5th) – based on multi-model-median risk values for each of the 17 scenario combinations. Numerical values in the upper right corners indicate the multi-model-median proportion (in %) of the European population that is at very high risk of heat stress, for each scenario combination. The colors of the frames indicate the plausibility of the scenario combination (no color (black) is given for combinations with baseline climate and/or baseline socioeconomic conditions).

respectively +30 M and + 15 M people at high/very high risk, hence affecting respectively 66.7% and 28.8% of the regional population. This negative influence is comparable to the consequences of the changes in climatic conditions expected under RCP2.6 and RCP4.5 (leading to respectively +14 M and + 31 M people at high/very high risk). Likewise, the negative effect of $SSP3_{EU}$ and $SSP4_{EU}$ in Eastern Europe (respectively +25 M and + 21 M people at high/very high risk) is found to be similar to that of RCP4.5 and RCP8.5 (respectively +22 M and + 30 M). In Scandinavia, the influence of changes in socioeconomic conditions – which lead to −0.7, +2.5, and + 2.2 M of people at high/very high risk under $SSP1_{EU}$, $SSP3_{EU}$, and $SSP4_{EU}$ respectively – are even likely to outweigh the influence of changes in heat hazard, leading to only +0.5 M, +0.9 M, and + 1.2 M of people at high/very high risk under RCP2.6, RCP4.5, and RCP85 respectively.

4. Discussion

4.1. Likeliness of the scenario combinations

The potentially possible combinations of a given SSP_{EU} with the different RCPs are not equally plausible, because some would require more ambitious mitigation policies than others (Kriegler et al., 2014; van Vuuren et al., 2013). The most likely combinations for each $SSPs_{EU}$ are $RCP2.6*SSP1_{EU}$, $RCP8.5*SSP3_{EU}$, $RCP4.5*SSP4_{EU}$, and $RCP8.5*SSP5_{EU}$ (Harjanne et al., 2014; Jevrejeva, 2013; Kok et al., 2015). Results (Fig. 5) show that the three latter all lead to a large increase in the proportion of people at very high risk of heat stress in Europe (respectively 48.4%, 32.6%, and 20.3%, compared to 0.4% currently), while $RCP2.6*SSP1_{EU}$ is the only likely combination that leads to fairly low heat-related health challenges (2.4% of the population at very high risk). $RCP4.5*SSP5_{EU}$ and $RCP2.6*SSP4_{EU}$ lead to moderated heat-related health challenges (14.3% and 20.2% of the population at very high risk), but are considered as "possible" only and would thus require ambitious mitigation policies to occur (SSP5EU/SSP4EU are more likely to lead to a RCP8.5/RCP4.5 world).

In brief, exploring the outputs of the risk assessment in light of the plausibility of the scenario combinations clearly illustrates that the future proportion of people at very high stress risk in Europe is most likely to increase significantly unless substantial political changes occur to rapidly and steadily shift the current socioeconomic development pathway towards sustainability, as depicted under $SSP1_{EU}$. Future heat-related challenges could be moderated to some extent by rapid technological progress to enhance human capital – as depicted under $SSP5_{EU}$ – combined with ambitious mitigation policies to limit the warming as expected under RCP4.5.

4.2. Influence of changes in vulnerability and exposure

One of the main benefits of developing climate and socioeconomic scenarios in parallel and of combining them afterwards into a scenario matrix is that it allows the exploration of the individual contribution (to future climate risk) of changes in climatic conditions and changes in socioeconomic conditions separately (Moss et al., 2010; van Vuuren et al., 2013). In this paper, we have particularly emphasized the impact that changes in vulnerability – as depicted in the four $SSPs_{EU}$ – have on future heat-related health challenges. Results (Fig. 6) show that changes in socioeconomic conditions considerably influence the future proportion of people at high/very high risk of heat stress, particularly in places

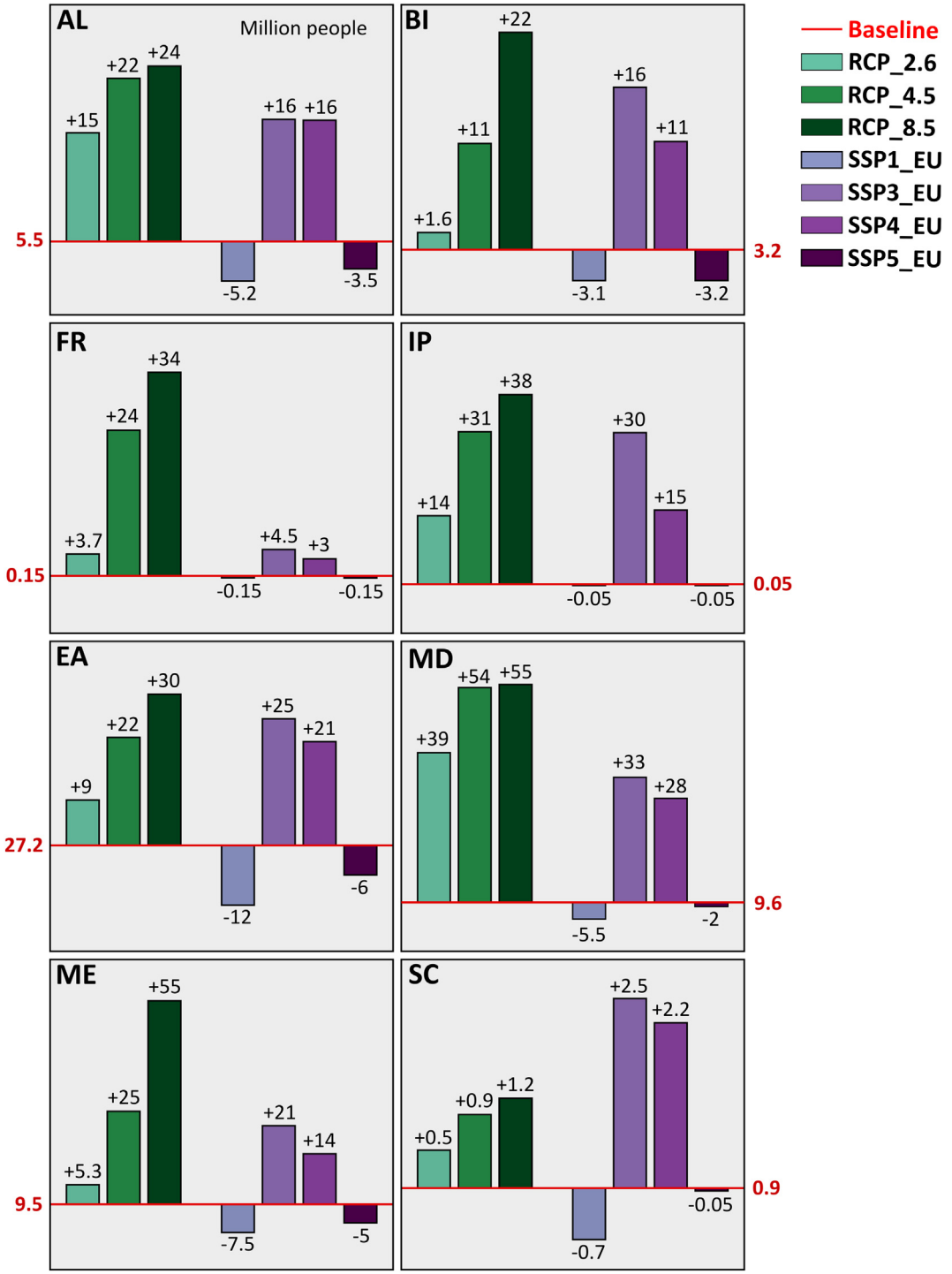

Fig. 6. Changes in millions of people exposed to high or very high heat stress risk compared to the baseline situation (in red), when assuming changes in climatic conditions alone – for each RCP – or changes in socioeconomic conditions alone – for each SSP_{EU} –, in each European sub-domains (AL = Alps; BI = British Isles; EA = Eastern Europe; FR = France; IP = Iberian Peninsula; MD = Mediterranean; ME = Mid-Europe; SC = Scandinavia). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where vulnerability shows substantial changes compared to baseline conditions.

To further investigate the influence of $SSPs_{EU}$ on future heat-related health challenges under different climatic conditions, we computed the difference – in terms of number of people at high/very high risk – between risk assessments that consider changes in socioeconomic conditions (*i.e.* RCPs*SSPs) and those that assume static socioeconomic conditions (*i.e.* RCPs*baseline). This was performed within each European sub-domain, for each SSP_{EU}, and under each future climatic conditions (*i.e.* under each RCP, exception made of the inconsistent RCP*SSP combinations).

Results (Fig. 7) show that the influence of the different $SSPs_{EU}$ on the future number of people at high/very high risk varies widely from one region to another, as well as from one SSP_{EU} to another, and depends on future climatic conditions. $SSP1_{EU}$ and $SSP5_{EU}$ have the potential to decrease drastically future heat-related health challenges,

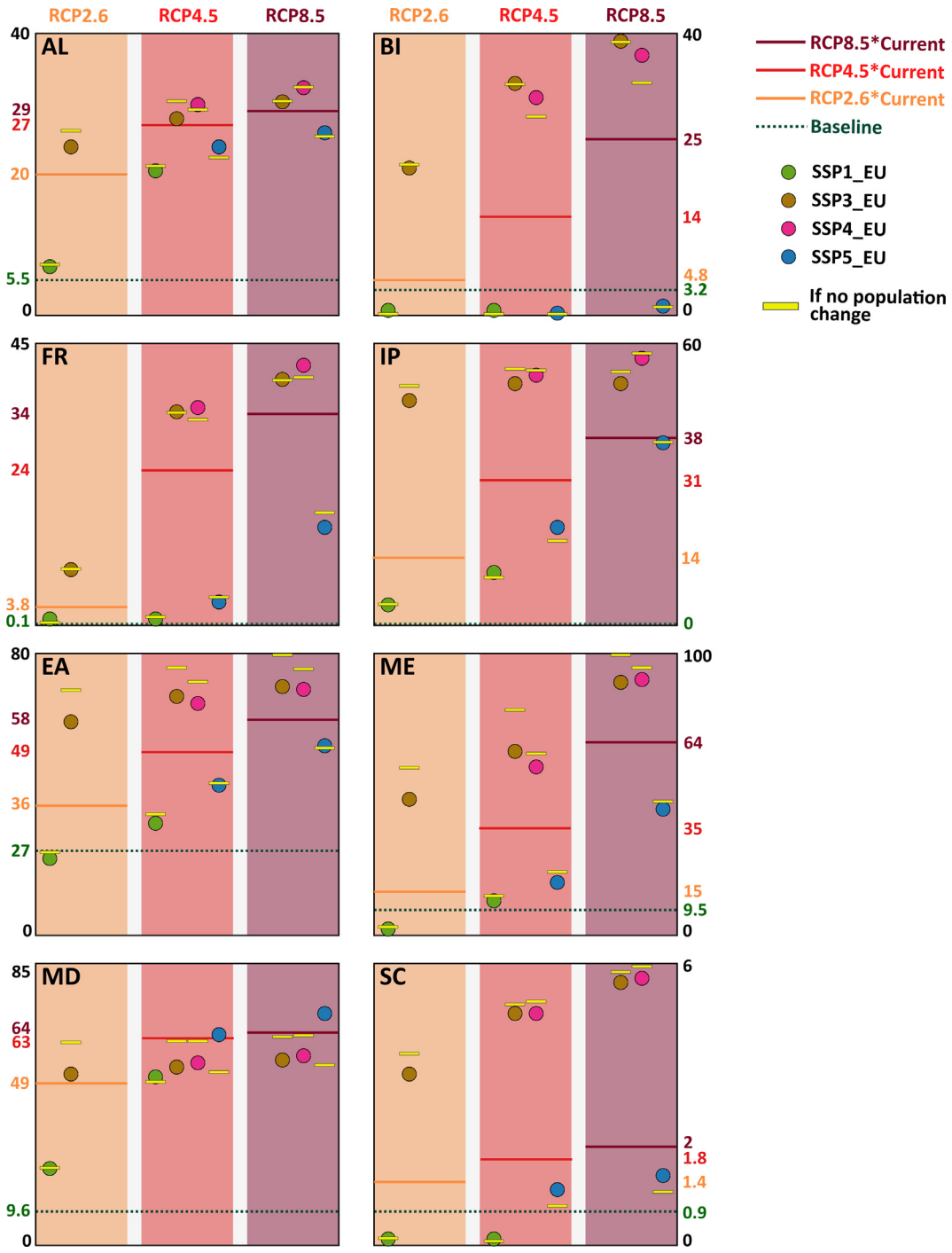

Fig. 7. Million people at high/very high risk per region, in the current situation (dotted green line – Baseline) and for the year 2050 assuming changes in climatic conditions only (horizontal lines, RCP*Current), changes in both climatic and socioeconomic conditions (circles, for each investigated combination of RCP and SSP_{EU}), and changes in climatic and socioeconomic conditions with fixed population (yellow bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

particularly in a warmer world as expected under RCP4.5 and RCP8.5 (for $SSP5_{EU}$ only). For instance, in most regions, these socioeconomic development pathways lead to a decrease in risk that is of comparable magnitude to the difference in risk level observed between RCP2.6 and RCP4.5 (in the case of $SSP1_{EU}$) or between RCP4.5 and RCP8.5 (in the case of $SSP5_{EU}$). In other words, the benefits (in terms of reduction of heat-related health challenges) of shifting towards socioeconomic pathways depicting a society with a low level of vulnerability are comparable to the ones of ambitious mitigation strategies that would enable reaching RCP2.6 rather RCP4.5 (or RCP4.5 rather than RCP8.5).

By contrast, the positive effect of limiting warming to the level expected under RCP2.6 or RCP4.5 can be completely counterbalanced and inhibited if the European socioeconomic development follows the pathways depicted in $SSP3_{EU}$ or $SSP4_{EU}$. Indeed, when considering RCP4.5, both $SSP3_{EU}$ and $SSP4_{EU}$ lead to an increase in the number of people at high/very high risk that is significantly higher than the decrease expected when shifting from RCP8.5 to RCP4.5. Even more importantly, because the socioeconomic development pathways depicted in $SSP1_{EU}$/$SSP5_{EU}$ and $SSP3_{EU}$/$SSP4_{EU}$ have an opposite influence on future heat-related health challenges, the benefits of shifting towards

$SSP1_{EU}$ or $SSP5_{EU}$ rather than towards $SSP3_{EU}$ or $SSP4_{EU}$ are remarkably large, under all climatic conditions. For instance, following the socioeconomic pathway depicted under $SSP4_{EU}$ ($SSP3_{EU}$) rather than the one depicted under $SSP1_{EU}$ ($SSP5_{EU}$) would lead to an increase in the number of people at high/very high risk of +30 M (+38 M) people in the British Isles, +34 M (+22 M) in France, +41 M (+12 M) in the Iberian Peninsula, and + 46 M (+47 M) in Mid-Europe, when combined with RCP4.5 (RCP8.5).

Finally, to further explore the individual influence of changes in exposure (*i.e.* population growth or decline), we computed the number of people at high/very high risk assuming no population change. Results show that changes in exposure have very little influence – compared to changes in vulnerability – on future heat-related health challenges in most regions and under most socioeconomic and climatic scenarios. In a very few cases, changes in exposure have a comparable influence to changes in vulnerability – *e.g.* the population decline in Eastern Europe and in Mid-Europe depicted in $SSP3_{EU}$ and $SSP4_{EU}$ substantially limits the increase in the number of people at high/very high risk in these areas.

4.3. Sensitivity analysis

To highlight the robustness of the results in relation to the methodological choices, we performed ten different risk assessments, of which (*i*) two included changes in the method employed to aggregate the determinants of risk, (*ii*) seven included changes in the choice of the RCM simulation, and (*iii*) one included a different definition of heat waves (see appendix J for the full details and results). Based on visual and statistical reasoning (Reckien, 2018), we showed that changes in the choice of the RCM simulation and of the definition of heat wave do not substantially affect the results, mainly because the heat hazard is spatially and temporally normalized before being combined with the vulnerability index and exposure to compute risk. Similar results are also obtained when using an additive approach – rather than a geometric aggregation – to combine the heat hazard and the vulnerability index, as well as when using a Principal Component Analysis (PCA) to determine the weight of the vulnerability determinants (rather than an approach with equal weights).

5. Conclusion

In this paper, we presented a European assessment of future heat-related health challenges based on multiple combinations of climate and socioeconomic scenarios, at high spatial resolution. In doing so, we also accounted for changes in future vulnerability under varying levels of socioeconomic development, whereas to date studies have only focused on changes in human or economic exposure. Informed by four European Shared Socioeconomic Pathways ($SSPs_{EU}$), we employed consistent projections up to 2050 of several socioeconomic variables – such as GDP *per capita* (Hurth et al., 2017), population distribution (Lückenkötter et al., 2017), urbanization (Terama et al., 2017), ageing (Terama and Clarke, 2016), education (KC and Lutz, 2017), pre-existing medical conditions, and social isolation (Rohat, 2018) – to explore future populations' abilities to prepare for, respond to, and recover from extreme heat events. Results showed that varying levels of socioeconomic development substantially influence future populations' vulnerability. Under $SSP1_{EU}$ and $SSP5_{EU}$, the vulnerability at the European level significantly decreases due to strong economic growth and significant investment in education and health, in line with recent evidence suggesting possible declines in vulnerability over time to climatic hazards (Bouwer and Jonkman, 2018). On the other hand, future vulnerability under $SSP3_{EU}$ and $SSP4_{EU}$ substantially increases, mostly due to a lack of education, the deterioration of public health, and gloomy or unequal economic growth.

By combining projections of vulnerability and exposure – under the four different $SSPs_{EU}$ – with projections of heat hazard – under three different RCPs –, we explored future heat-related health challenges in Europe and accounted for the full range of uncertainties in both climate change and socioeconomic development. Results revealed that the proportion of the European population at very high risk of heat stress will show a steady increase under three of the four most plausible futures, namely RCP8.5*$SSP5_{EU}$, RCP8.5*$SSP3_{EU}$, and RCP4.5*$SSP4_{EU}$, reaching respectively 20.3%, 32.6%, and 48.4% of the whole population (compared to 0.4% currently). Such a drastic increase is in line with recent findings (Forzieri et al., 2017). Future heat-related health challenges will remain low at the European level only if substantial political changes occur to rapidly and steadily shift towards sustainability – as depicted under $SSP1_{EU.}$ Ambitious mitigation policies associated with rapid technological progress to enhance human capital (as depicted under RCP4.5*$SSP5_{EU}$) could also moderate future heat-related health challenges to some extent.

Such threats to public health will be unevenly distributed across Europe, with Scandinavia and the Mediterranean region showing respectively the lowest and highest heat-related health challenges under most of the scenario combinations. In the latter region, but also in the Southern part of Eastern Europe and in the Iberian Peninsula, a strong increase in heat hazard (as expected under RCP8.5) combined with unequal socioeconomic development and/or gloomy economic conditions associated with a disintegration of the social fabric (as depicted in $SSP3_{EU}$ or $SSP4_{EU}$) would lead to a world in which the near-totality of the population of these regions is at high or very high risk of heat stress. The spatial clusters of high risk identified in this study – when assuming fixed socioeconomic conditions – are consistent with previous climate risk assessments at the European scale (EEA, 2016).

Leaning on the scenario matrix architecture (van Vuuren et al., 2013), we also explored and isolated the influence of varying levels of socioeconomic development on future heat-related health challenges. Results showed that such influence varies from one region to another and depends on the socioeconomic and climate scenarios under consideration. We highlighted that socioeconomic development pathways aiming towards a socially equitable Europe where the emphasis is on human well-being and education (as depicted in $SSP1_{EU}$) or towards a strong Europe with rapid technological progress to enhance human capital (as depicted in $SSP5_{EU}$) have the potential to significantly alleviate future heat-related health challenges, particularly when considering a warmer world as expected under RCP4.5 and RCP8.5. In certain regions (*e.g.* the British Isles, Mid-Europe, and France), the benefits of shifting towards the latter socioeconomic development pathways are comparable to a shift from high-end (RCP8.5) to low-end (RCP2.6) climate scenarios. Conversely, the benefits of ambitious mitigation strategies could be annihilated by socioeconomic pathways comparable to the ones depicted in $SSP3_{EU}$ or in $SSP4_{EU}$. This ability of varying levels of socioeconomic development to reduce (or increase) future heat-related challenges is due primarily to their impact on vulnerability – changes in population exposure being only of secondary importance –, confirming recent results in the field of hunger risk in which social vulnerability plays a major role (Davenport et al., 2017; Kamali et al., 2018). We therefore emphasize here that socioeconomic development pathways should not be viewed solely as potential means to reach a given level of radiative forcing, but also as key determinants of future climate risks, particularly when considering their impact on future populations' vulnerability – and not only on exposure. This sheds light on the undeniable necessity to consider the future state of vulnerability – and its uncertainties under varying levels of socioeconomic development – when assessing future heat-related health challenges and designing health adaptation strategies.

Although the findings of this study are robust in response to changes in climate models, in the definition of, and in indicators' aggregation methods, they should be accompanied by a certain number of caveats. Firstly, the socioeconomic projections – and their spatial disaggregation – are associated with a number of uncertainties, often linked to the modeling approach (Terama et al., 2017) and to the downscaling

procedure (Rohat, 2018). Using different sources of socioeconomic projections (for the same set of $SSPs_{EU}$) would help to properly propagate this source of uncertainty into the risk framework. Secondly, although informed by past studies, the selection of the drivers of vulnerability remained subjective – due to the lack of empirical data – and certain important determinants were not taken into account, such as the legacy component (Fouillet et al., 2008), the use of air conditioning, and acclimatization. Thirdly, the heat index (*HWDs*) does not account for single hot days that can also cause heat-related excess deaths, so may underestimates heat risk. Finally, the choice of a threshold level of 25 °C is debatable and might have led to an underestimation of future risk, particularly in Northern Europe, where recent studies suggest heat-related mortality at temperature levels below 25 °C (Åström et al., 2016).

While this paper constitutes a step towards a better understanding of the influence of changes in vulnerability – under varying levels of socioeconomic development – on future heat-related health challenges, more diverse and consistent projections of key determinants of vulnerability under different socioeconomic development pathways should open broader opportunities to better quantify their influence on the wide range of future climate risks (Wilbanks and Ebi, 2014), at various spatial scales and in different regions. Further research is also needed to explore ways to consider future adaptation strategies under the SSPs (Anderson et al., 2016). Such adaptation strategies could be dealt with as a third dimension (Petkova et al., 2016) through adaptation pathways or could be accounted for by means of concrete adaptation options and policies directly embedded within each SSP.

Further research could make use of the scenario matrix architecture to explore the efficiency of the adaptation strategies under multiple climatic and socioeconomic conditions and to identify the most suitable strategies for reducing heat-related health challenges under all plausible future scenario combinations.

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Appendix A-J. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2018.09.013.

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